High Actuator Count MEMS Deformable Mirrors for Space Telescope

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NASA SBIR PHASE I
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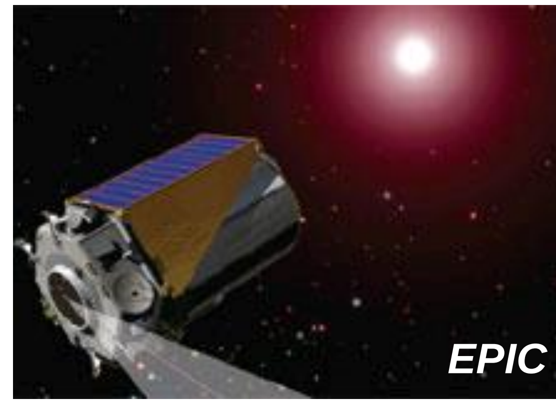
Outline

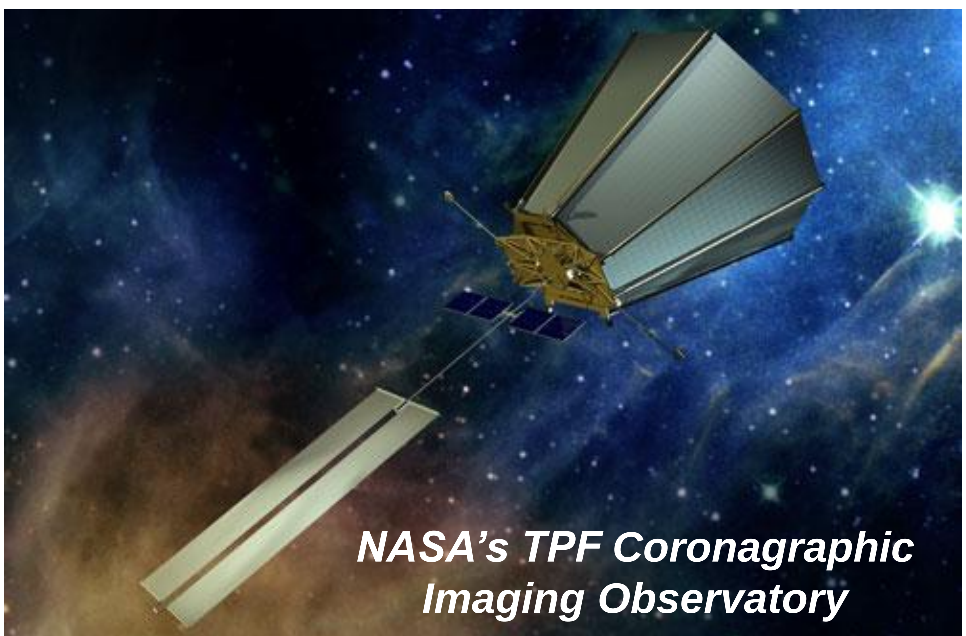
- MEMS DM Space telescopes applications
- Background on MEMS DMs
  - Architecture
  - Performance
- 1027 TTP device
    - 331 element DM
    - Yield
    - Surface Figure
- Multiplexing drive electronics
  - Description of current electronics
  - New Multiplexing drive electronics development

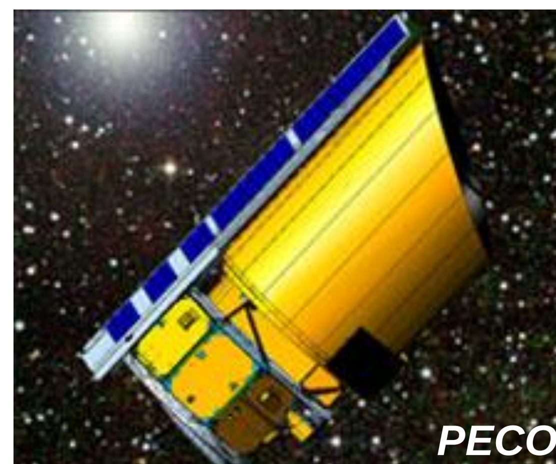
Applications for MEMS DMs in Space Telescopes

- Correction of static and slow moving (thermal) aberrations in space-based optical imaging systems
  - Astronomy – Direct Planet Detection
    - High Contrast Imaging
  - Astronomy/Reconnaissance
    - Correction of surface figure errors in Light weight primary mirrors



Extrasolar Planetary Imaging Coronagraph





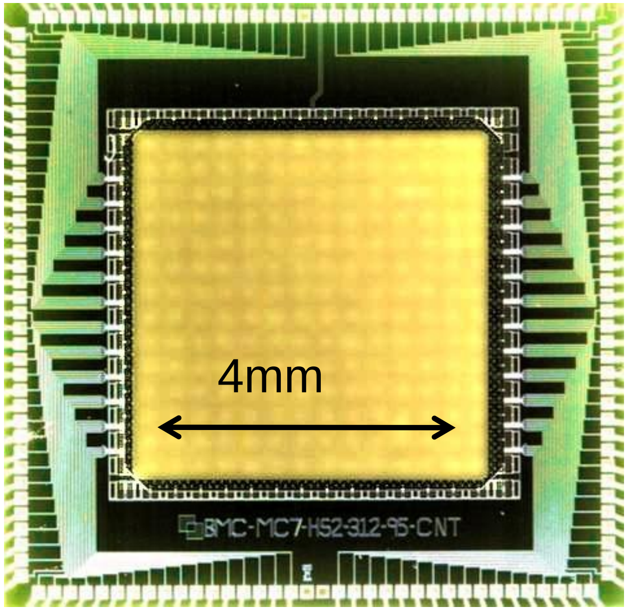
Pupil-mapping Exoplanet Coronagraphic Observer

Why MEMS for DMs?

Design
Smaller size/weight/power needed for space-based AO
Inherently scalable to larger arrays (**~4000**) needed for large telescope AO

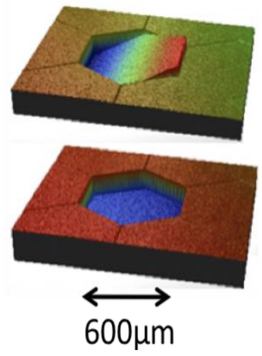
Manufacturability
10x Lower cost (**~$150/actuator**) than macroscale devices
Batch produced (vs. manual assembly)

Performance
- No hysteresis
- Reliable
- Fast
- Predictable
- Polarization and wavelength insensitive



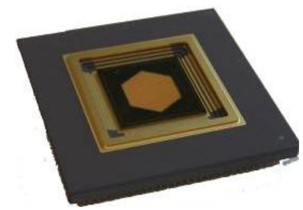
The advantages of these MEMS DMs have inspired a new generation of imaging instruments, and laser beam control systems

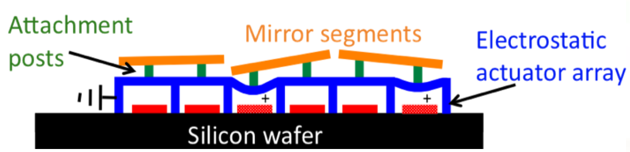
NASA SBIR Programs

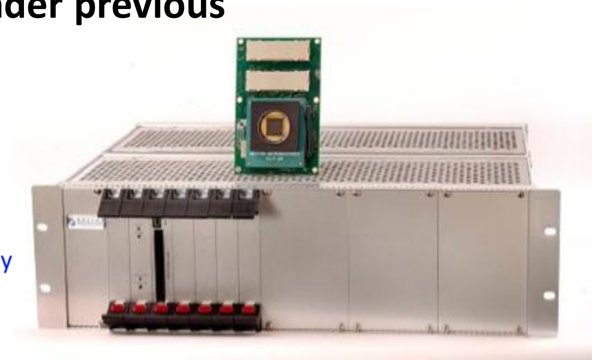


331 Segment, 993 Actuators
Tip-Tilt-Piston DM

Developed for JPL Coronagraph under previous SBIR Program

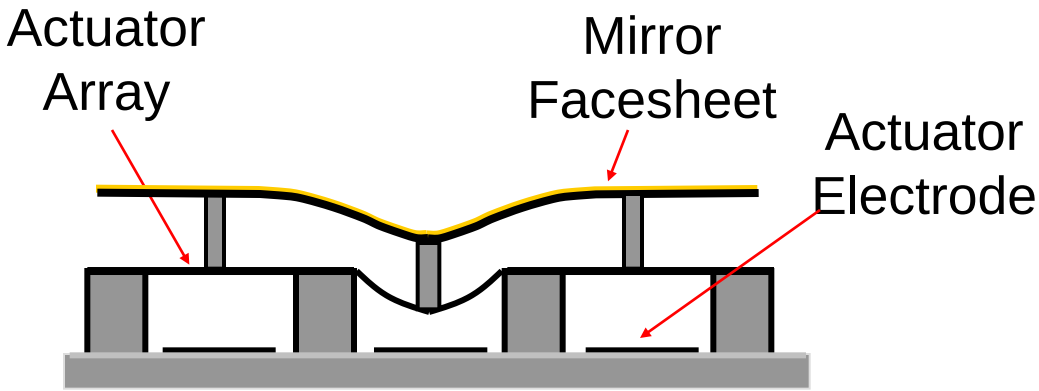






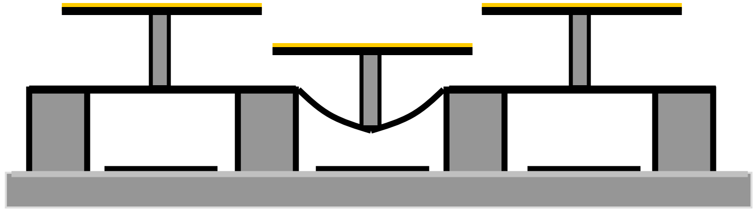
- **Enhanced Fabrication Processes Development for High Actuator Count Deformable Mirrors (Phase I, Contract #NNX10CE09P)**
  - **Objective:** Advance manufacturing science and technology to improve yield and optical surface figure in large, high-actuator count, high-resolution deformable mirrors required for wavefront control in space-based high contrast imaging instruments (target: 3081 actuator, 1027 segment tip/tilt/piston DM)
- **Compact Low-Power Driver for Deformable Mirror Systems (Phase I, Contract #NNX10CE08P)**
  - **Objective:** develop an ultra-low-power multiplexed electronic driver for high-resolution deformable mirror systems

BMC MEMS DM Architecture



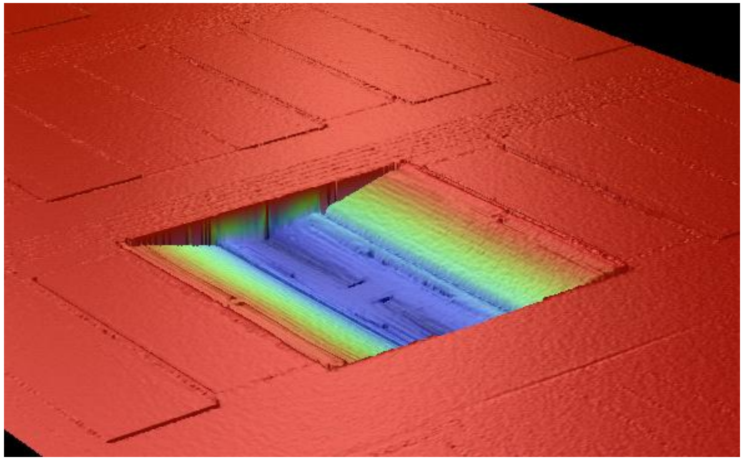
Continuous mirror (smooth phase control)

- Localized Influence Function
- Hysteresis-Free
- Scalable Architecture

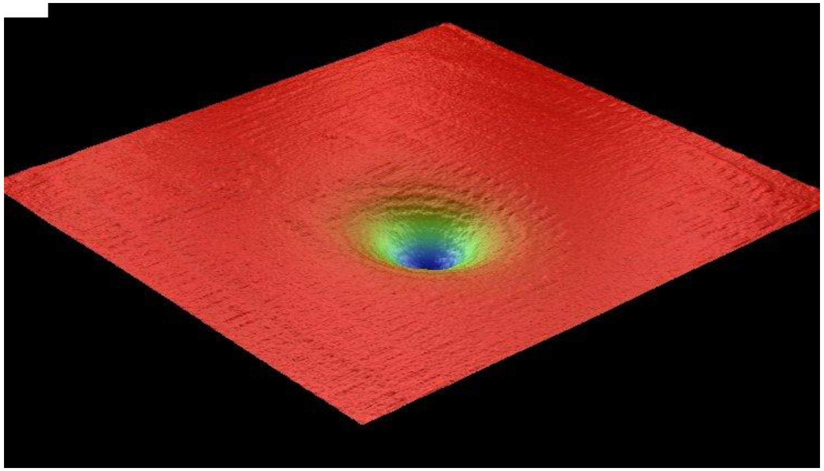


Segmented mirror (uncoupled control)

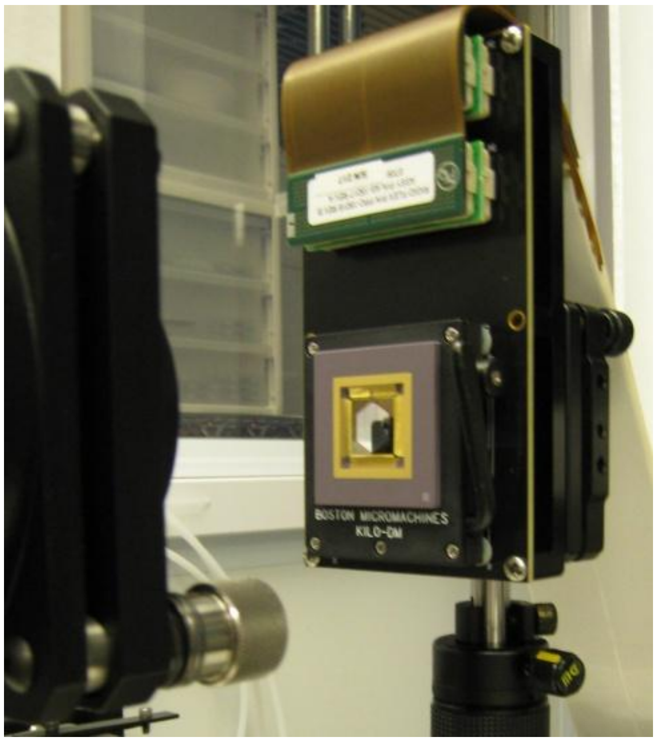
Deflected Actuator

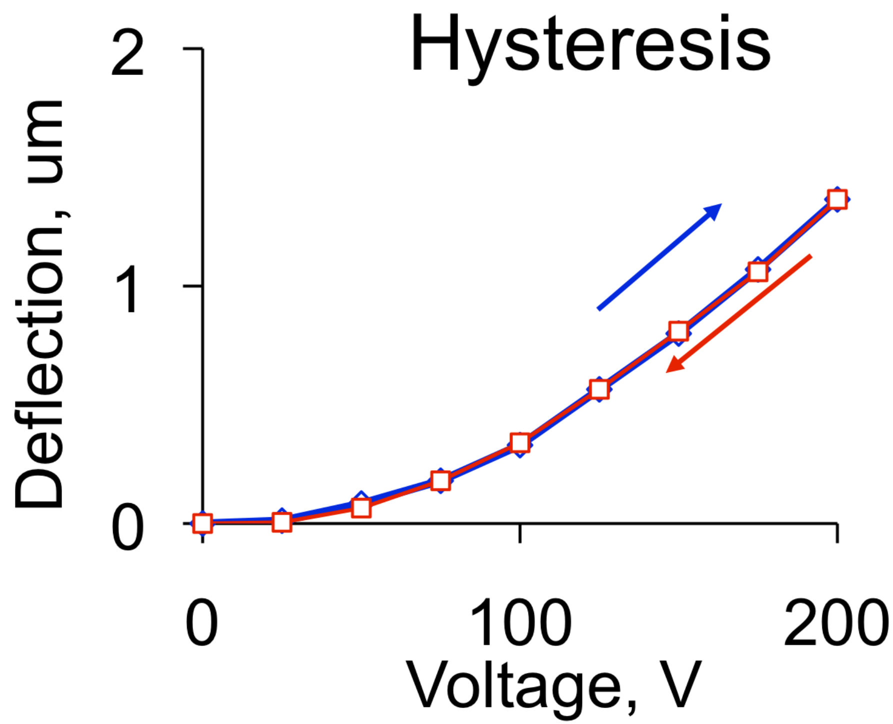


Deformed Mirror Membrane

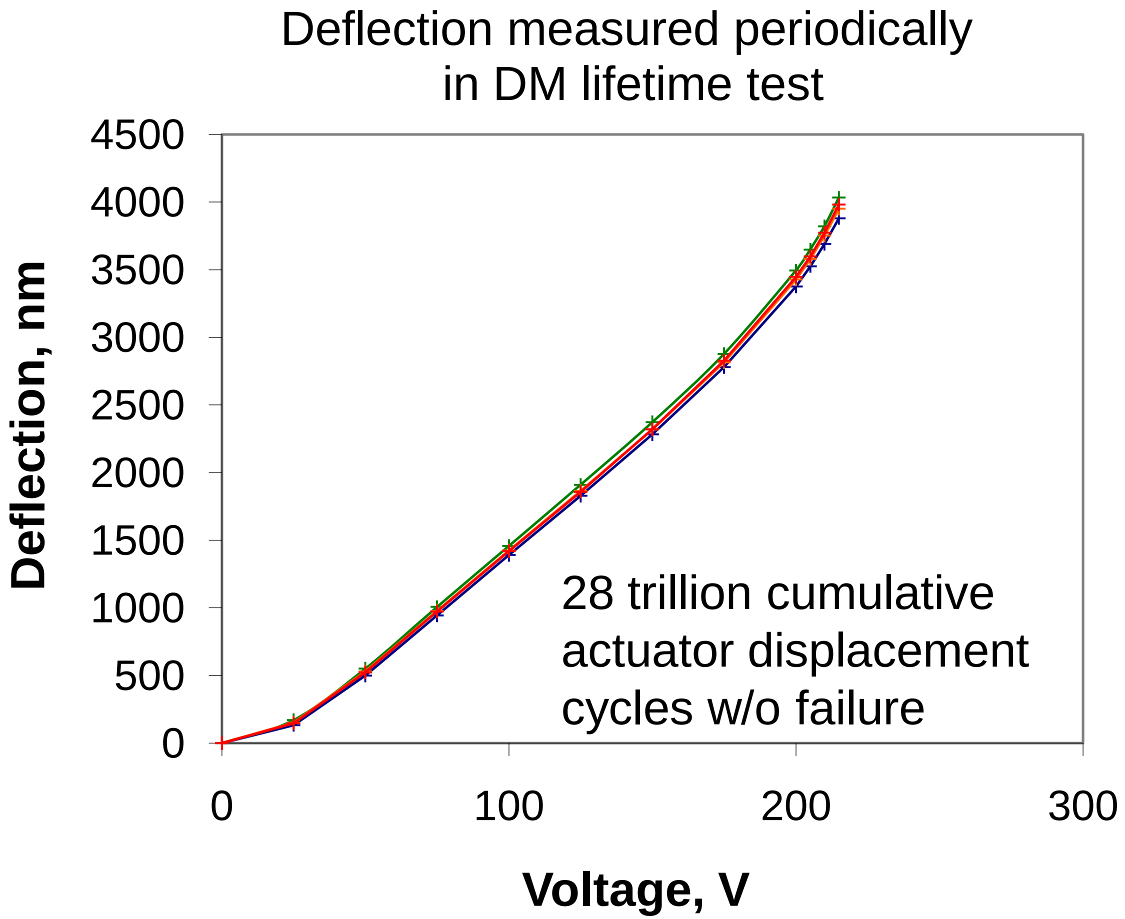


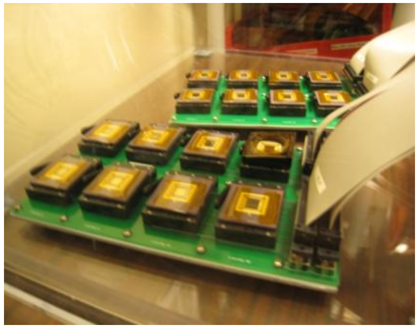
MEMS DMs exhibit no hysteresis

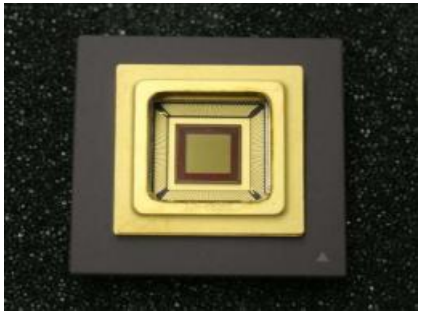




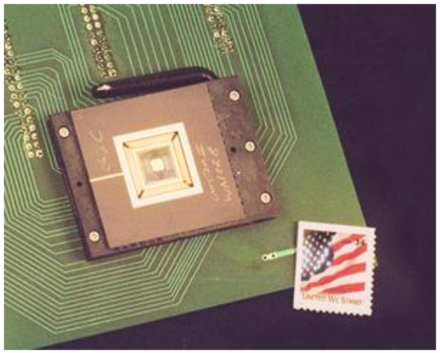
MEMS DMs Reliable





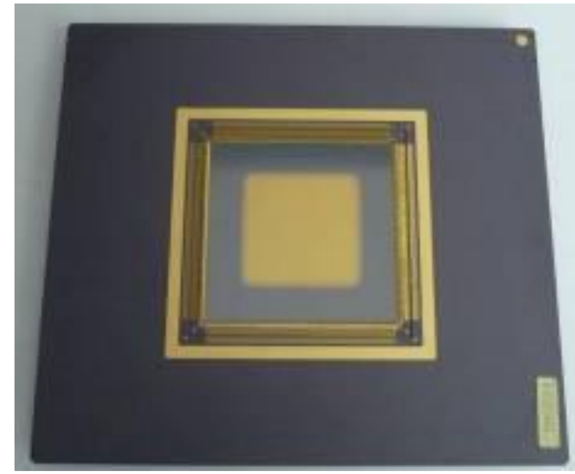


Evolution of BMC MEMS DMs



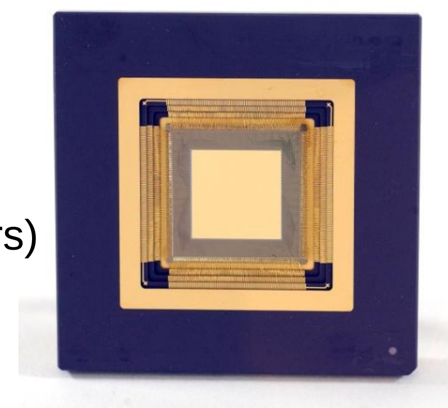
Y2000
2µm stroke
(140 actuators)

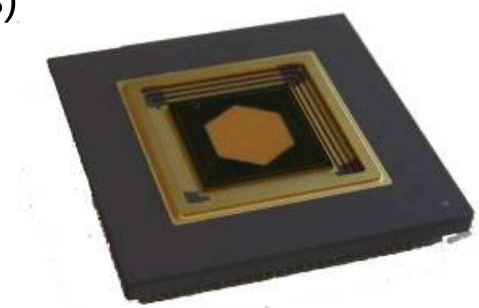
4µm stroke – Y'04
6µm stroke – Y'07
(140 actuators)



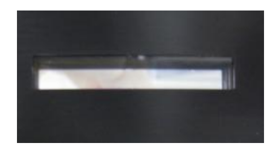
Y'10
4µm stroke
(4092 actuators)

Y'03
2µm stroke
(1020 actuators)
NASA SBIR





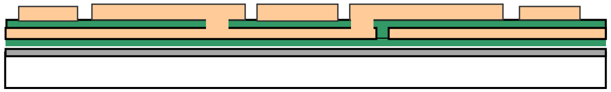
Y'08
2µm stroke/6mrad Tip & Tilt
(993 Actuators)
NASA SBIR



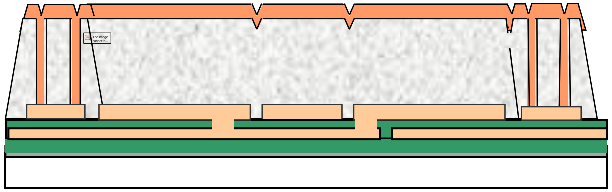
Y'09
2µm stroke 1-D Array
(1x140 act.)

MEMS DM Fabrication Process

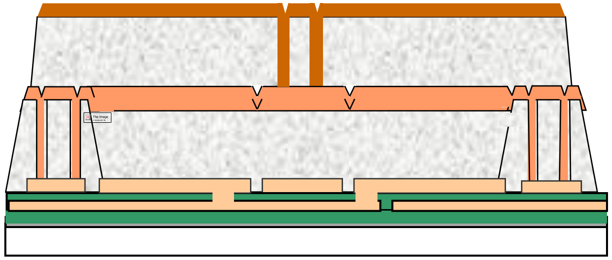
(deposit, pattern, etch, repeat)



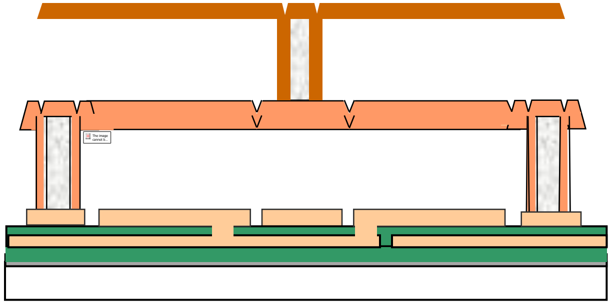
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)



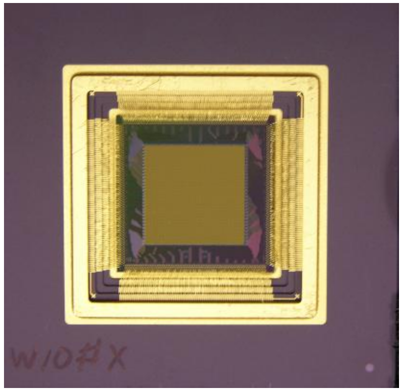
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



Mirror membrane:
oxide (spacer) and polysilicon (mirror)



MEMS DM:
Etch away sacrificial oxides in HF, and deposit reflective coating

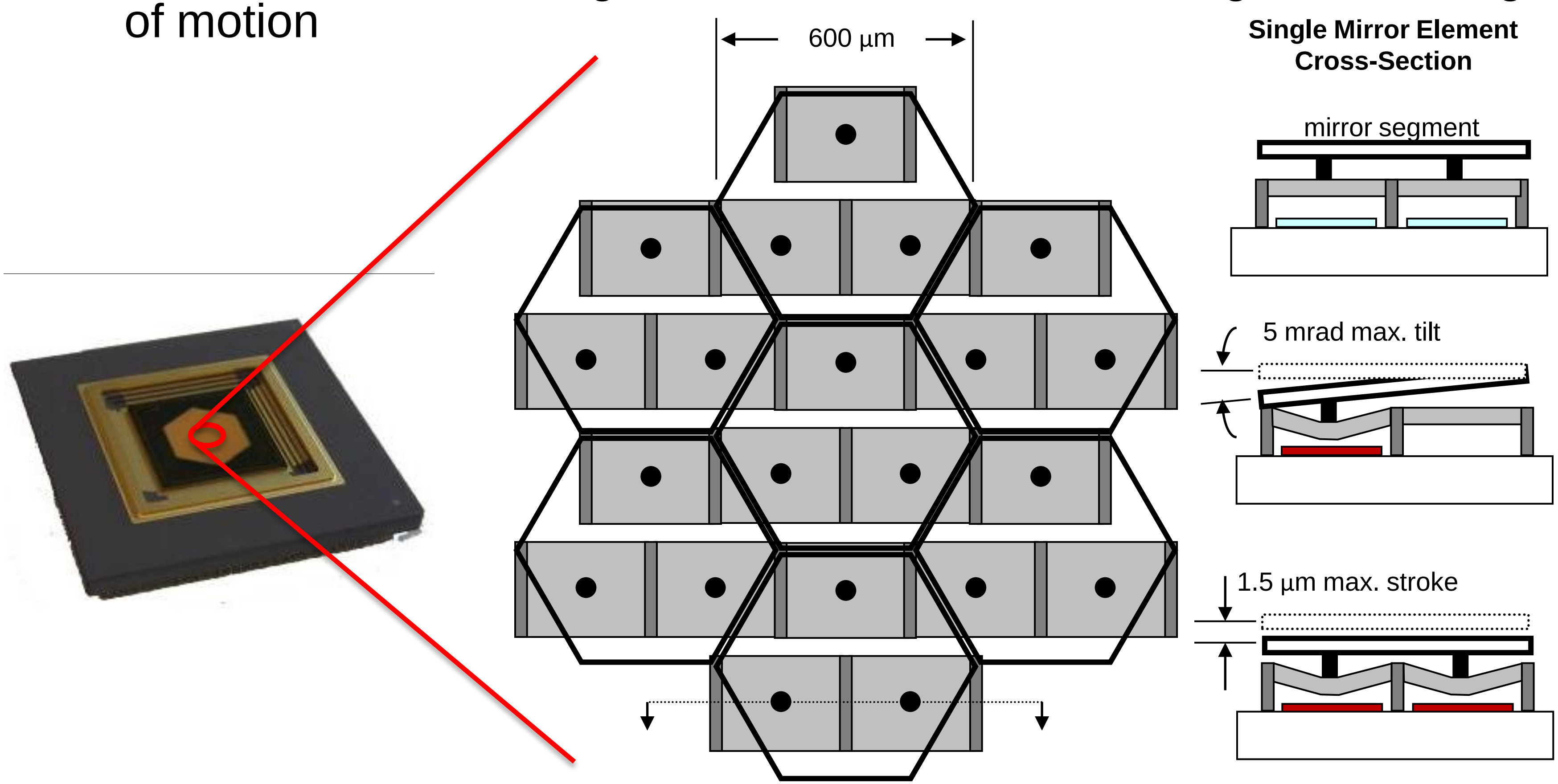


Electrical Interconnects:
Die attach and wirebond to ceramic chip carrier

Batch fabrication: 20 wafers per batch, 3-100 devices/wafer (depending on die size)

Tip-Tilt-Piston DM Overview

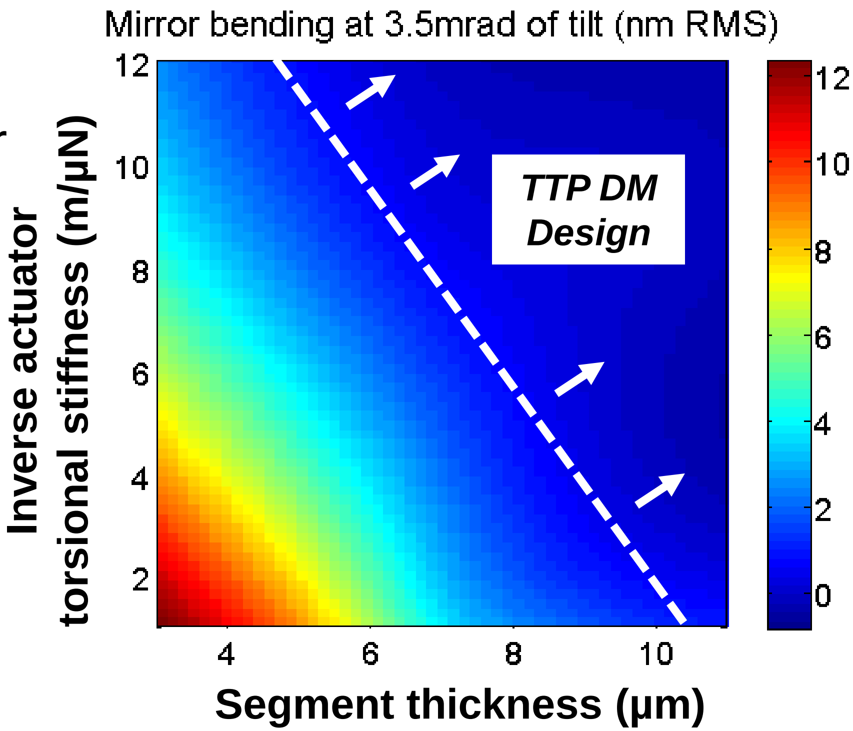
- Application: *Visible Nulling Coronagraph*
  - DM provides instrument with phase control using piston motion and amplitude control using tip-tilt motion
- Tip-tilt-piston degrees of freedom provided by three piston-only electrostatic actuators
- <10nm RMS mirror segment flatness achieved throughout full range of motion



Fabrication of Ultra-Flat MEMS DMs

Challenges:

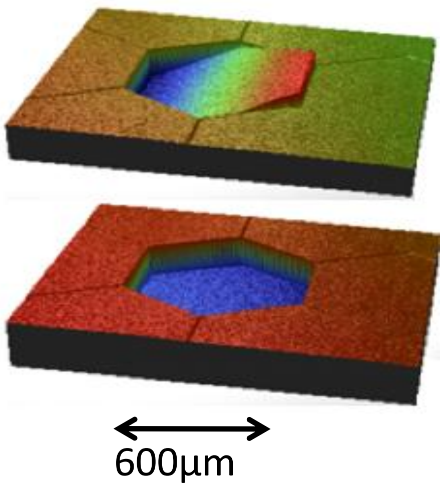
1. Mirror segments **bend** during actuation due applied moments from the actuator post connections
2. Mirror segments **curl** after release due to embedded stress gradients in the polysilicon layer
3. Optical quality is reduced by **print-through** of underlying layers

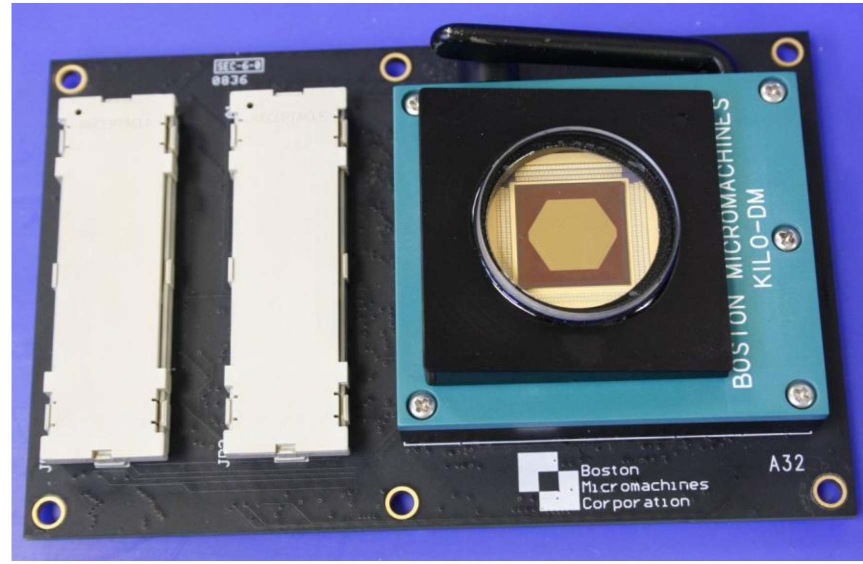


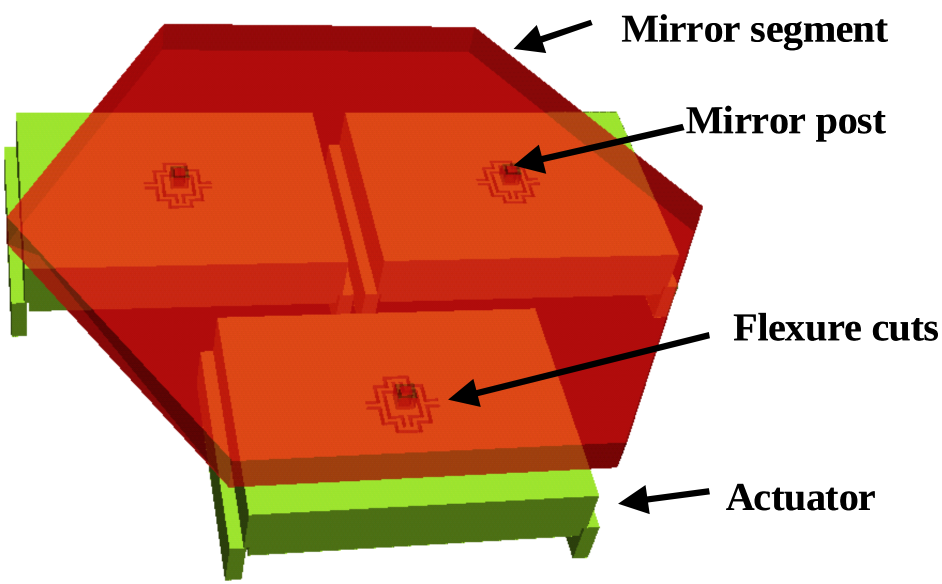
Solutions:

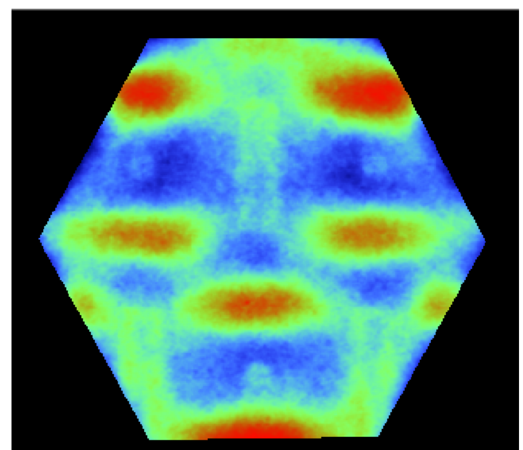
1. Bending-
   - **a) Resist** applied bending moments => increase rigidity with mirror thickness
   - **b) Reduce** applied bending moments => decrease actuator torsional stiffness
2. Counteract residual stress gradients through anneals of mirror polysilicon
3. Deposit thicker polysilicon for additional polishing to reduce print-through

331 segment TTP MEMS DM







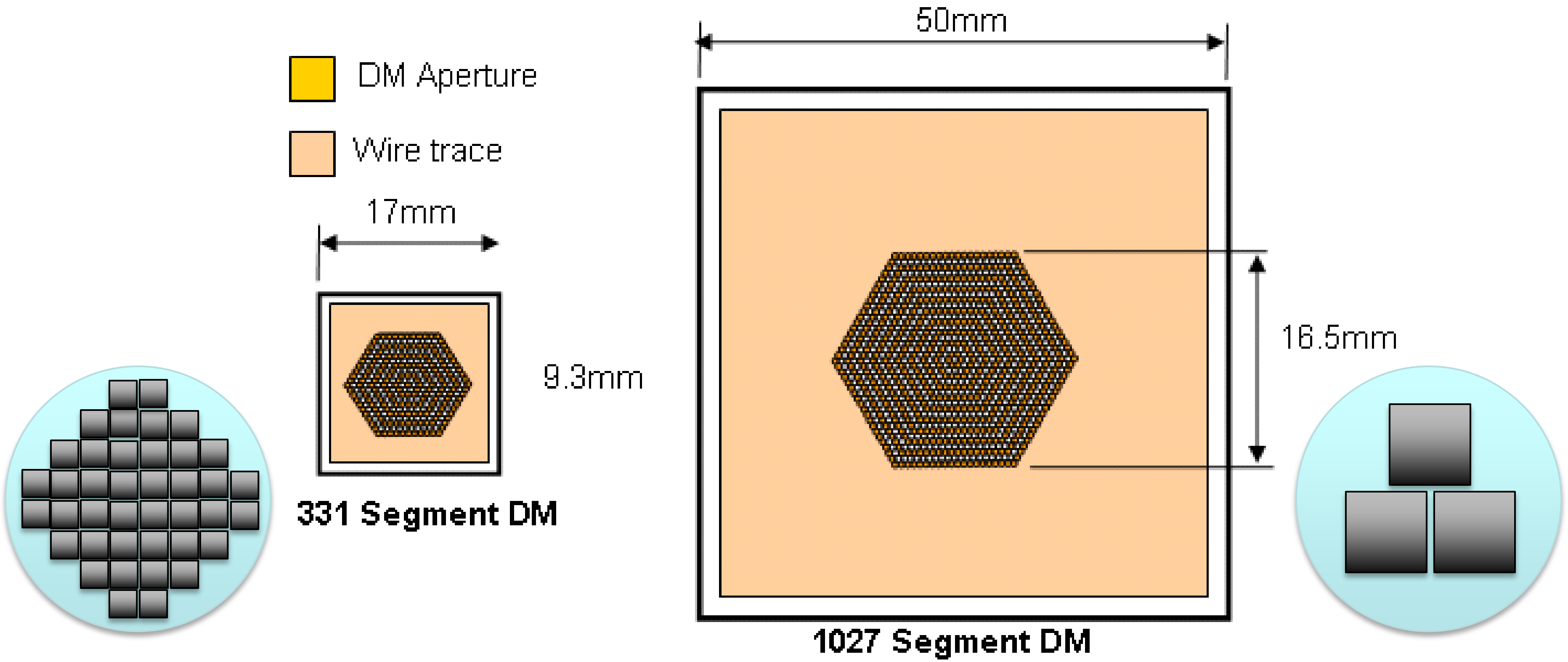


6nm RMS over 600µm segment

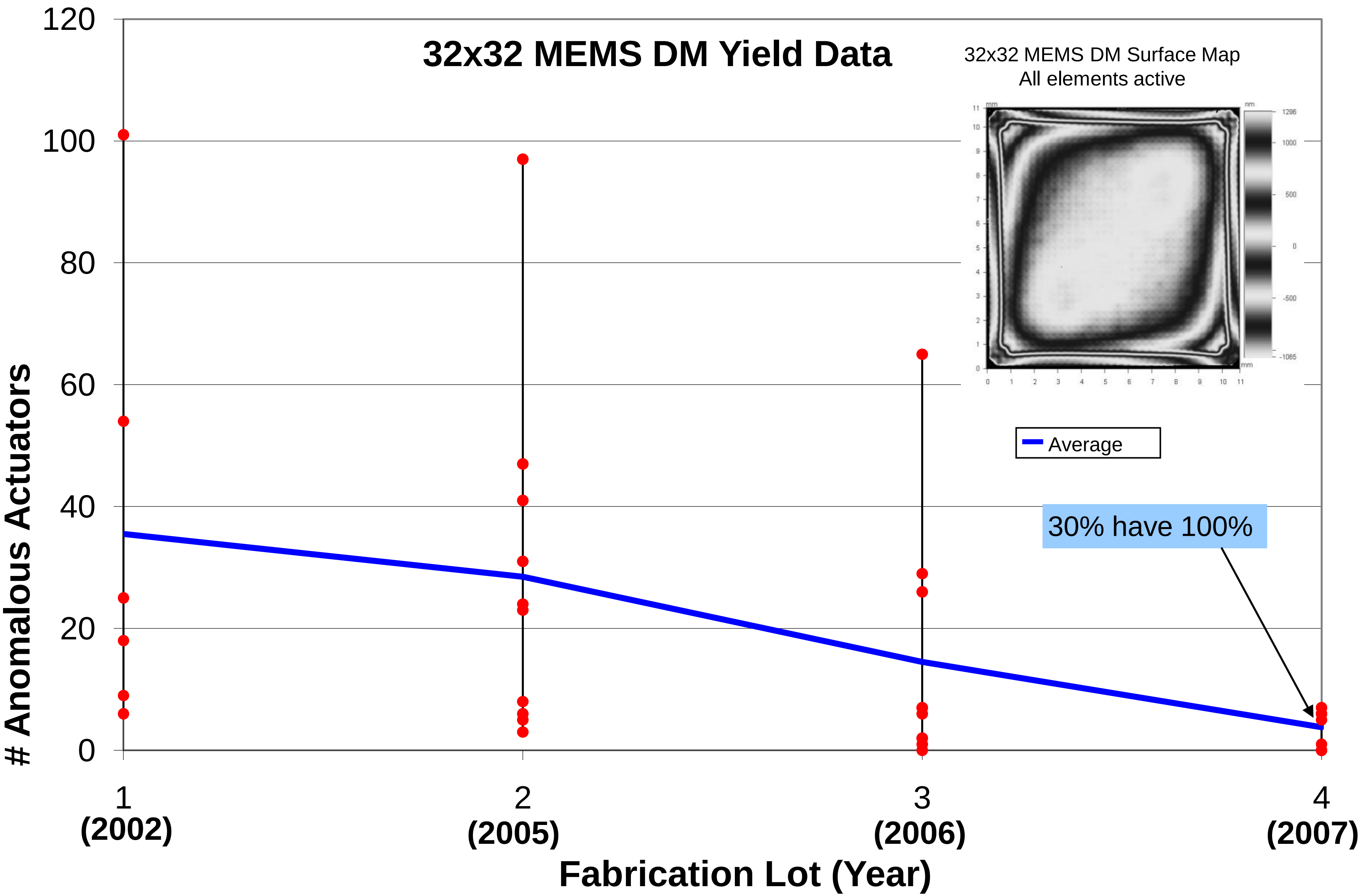
Delivered to NASA, (JPL HCIT) 2008

1027 Element Tip-Tilt-Piston MEMS DM

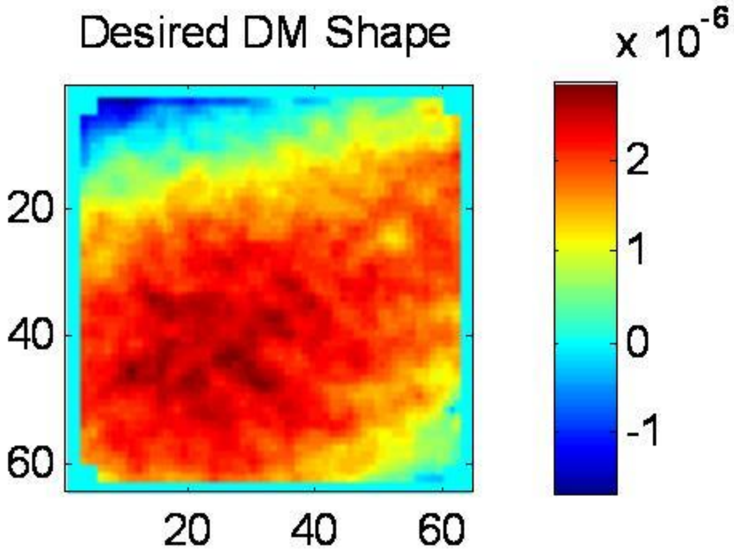
- Scale up mirror segments/actuators from 331/993 to 1027/3081
- Device architecture and fabrication process fundamentally scalable
- Challenge:
  - Managing inherent microscopic manufacturing defects (function of die area)
  - Controlling surface figure errors resulting from substrate bow and polishing

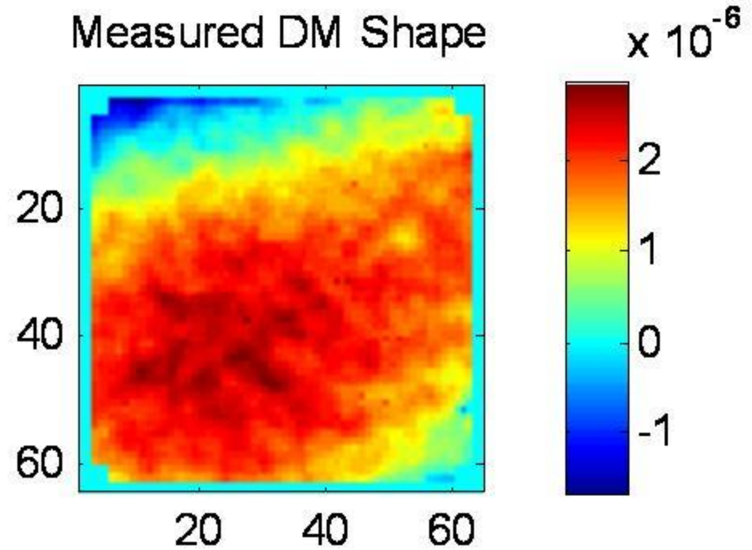


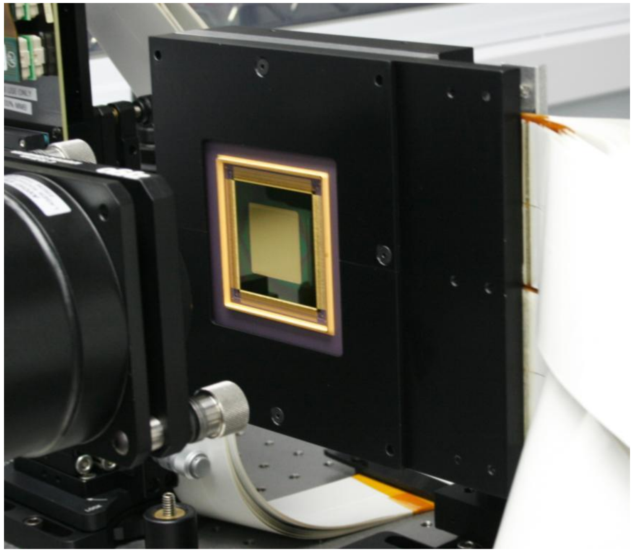
DM Actuator Yield



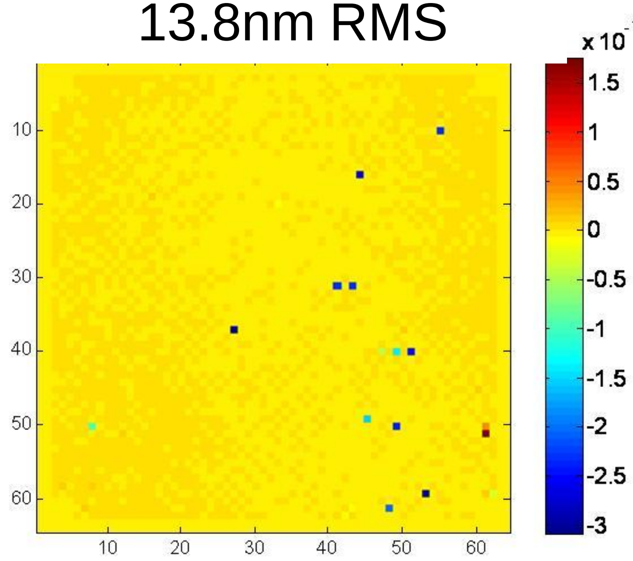
4092 Element DM Actuator Yield





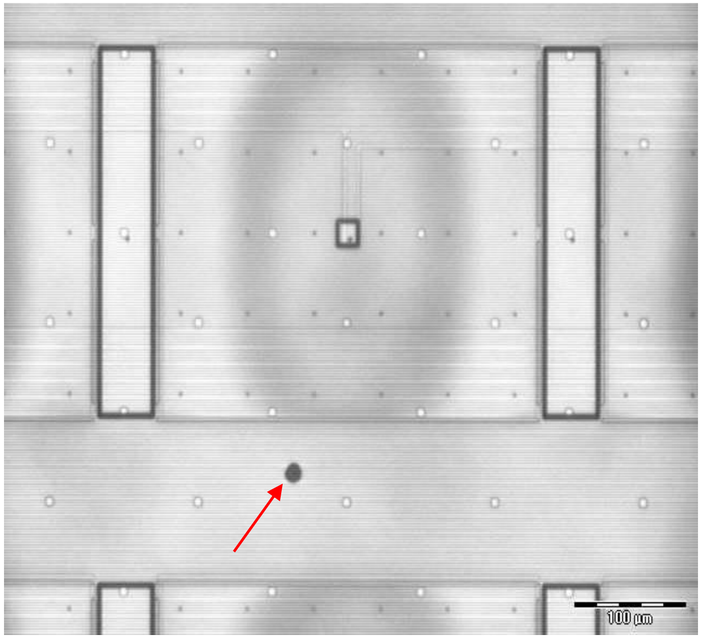


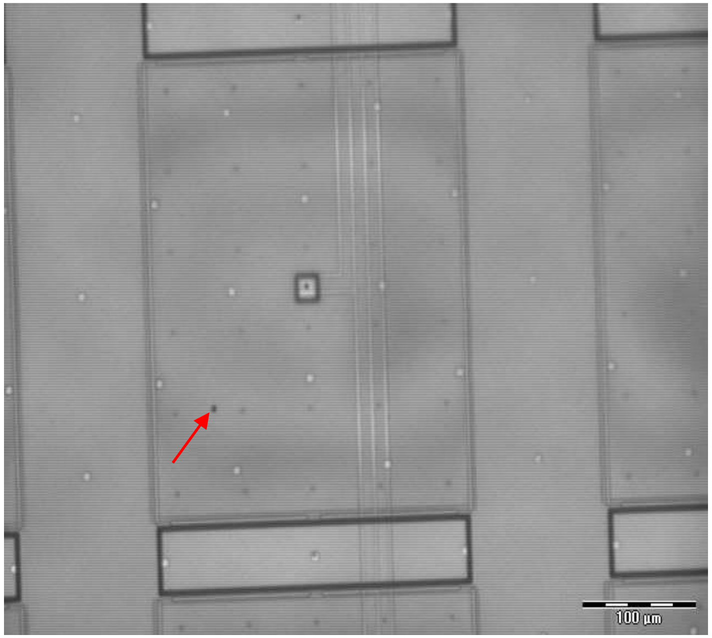
Residual Error:
13.8nm RMS



DM Actuator Yield :
>99.4%

Fabrication Process Defect Related Yield Issues



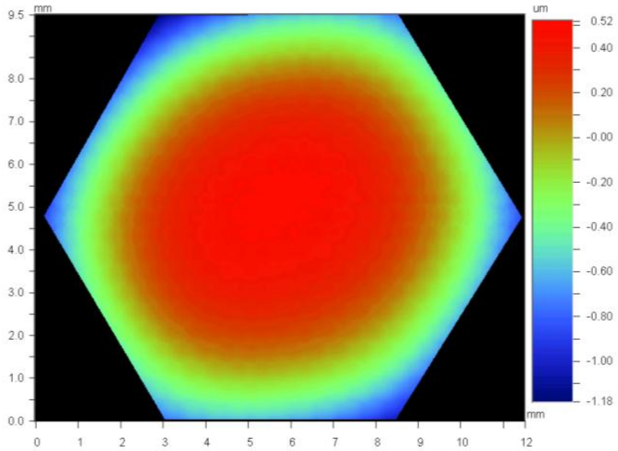


- Microscopic embedded particles are introduced during material deposition processes
  - electrical shorts (inactive/coupled actuators)
  - Surface figure defects
- Enhanced fabrication methods and design changes investigated in SBIR program to mitigate defect count and effects

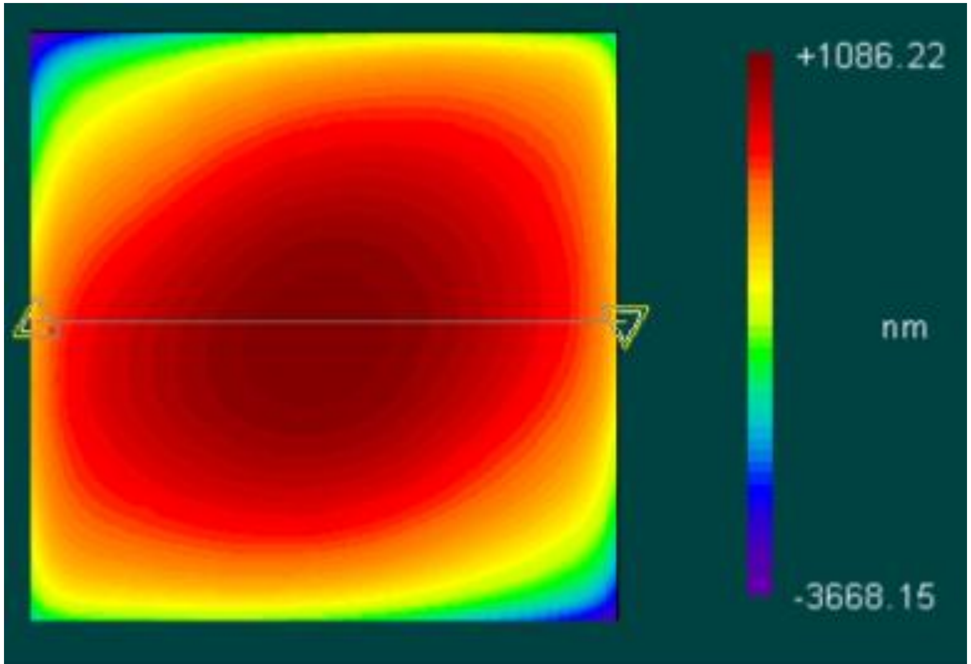
DM Surface Figure

- Surface Micromachined devices conform to substrate figure
  - Imbalance of front and backside film thickness results on wafer bow
  - Wafer bow of 50m ROC typical at end of manufacturing process
- New thin film deposition processes being developed to reduce wafer bow to 300m ROC

331 element DM Active Aperture figure error (P-V):~1μm

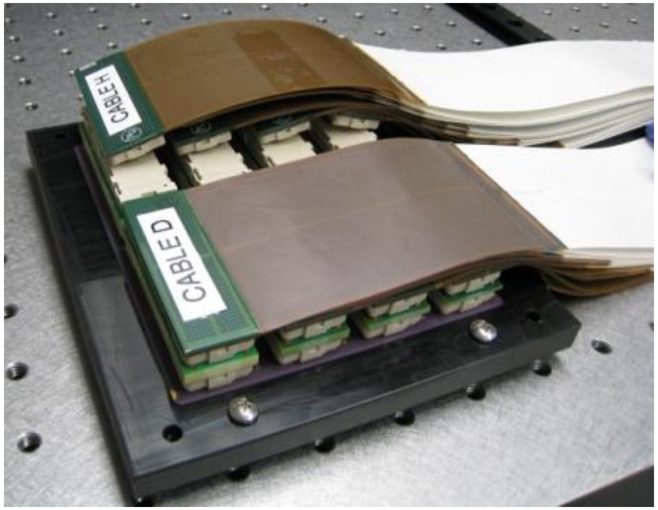


4096 element DM Active Aperture Figure Error (P-V): ~3.5μm



DM Drive Electronics

- Existing DM drive electronics using single DAC and amplifiers for each DM drive channel
- MEMS DM actuator is a capacitor – most power consumed driving high voltage amplifiers & DACs
- Space-based platforms require low power, more compact , and light weight electronics

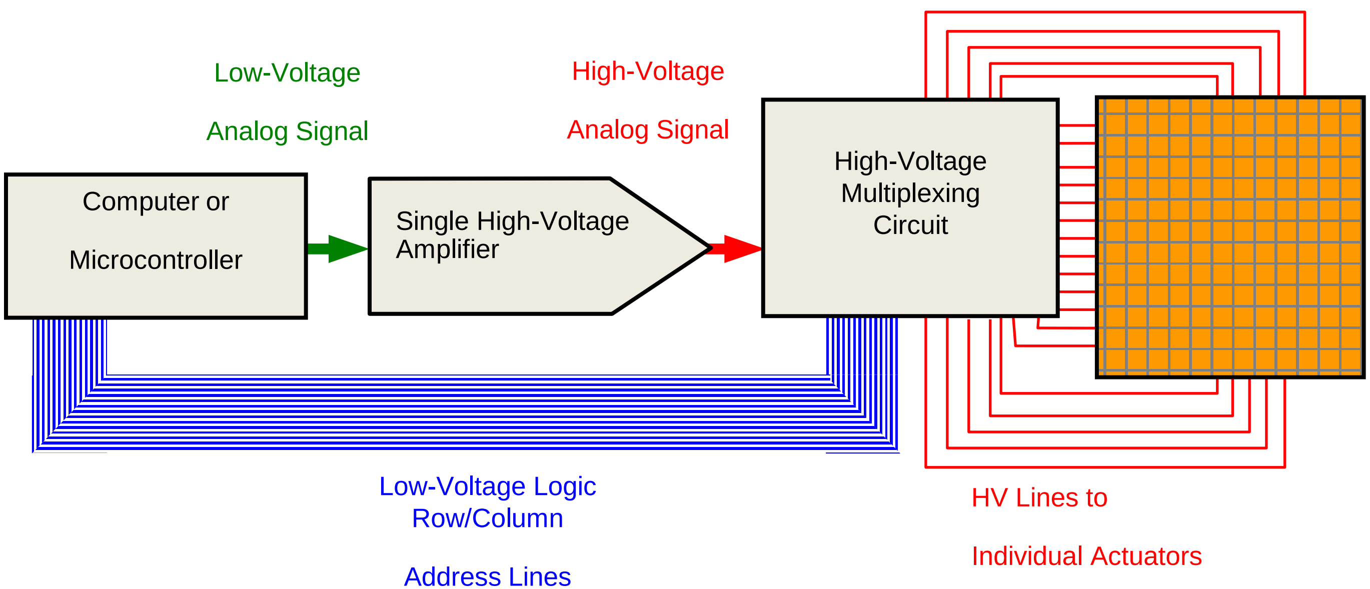


MEMS DM Driver Specification

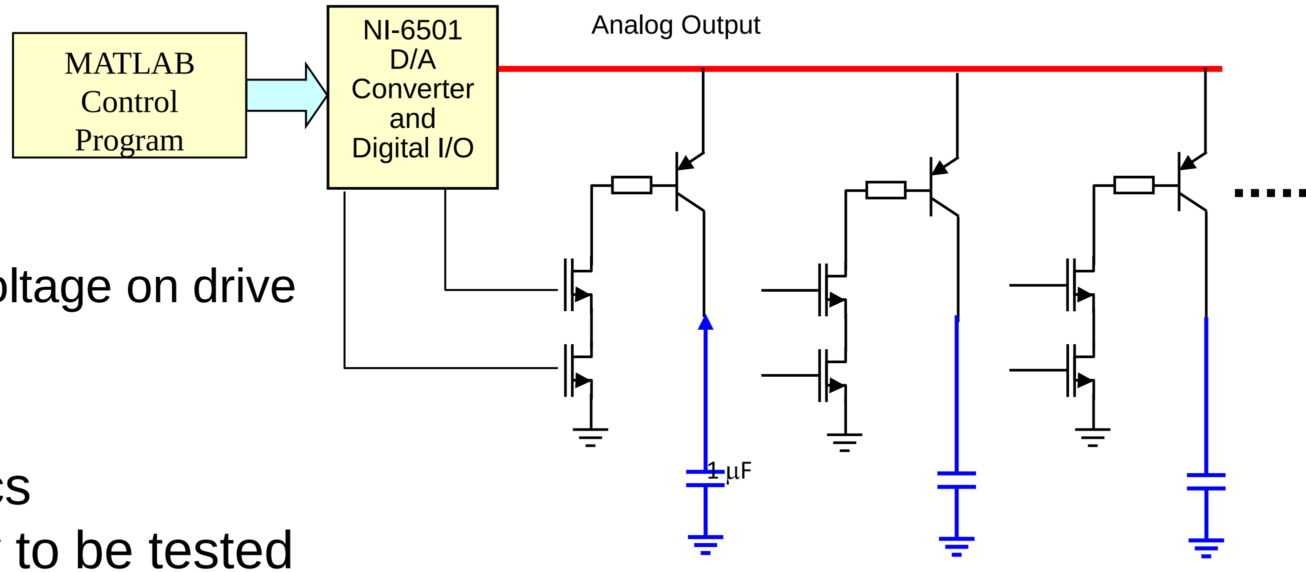
- # Channels: 4,096 channels
- Power Consumption: 80W (typ)
- Resolution: 14-bit
- Mass (w/ cables): 13.6kg
- Max Frame Rate: 24kHz
- Size: 3U Chassis (5.25” x19” x14”)

Multiplexed Drive Electronics

- Phase I SBIR aims to develop new multiplexed drive electronics
  - Reduce power by 2 orders of magnitude
  - Reduce size by order of magnitude
  - 16-bit resolution (0-300V)

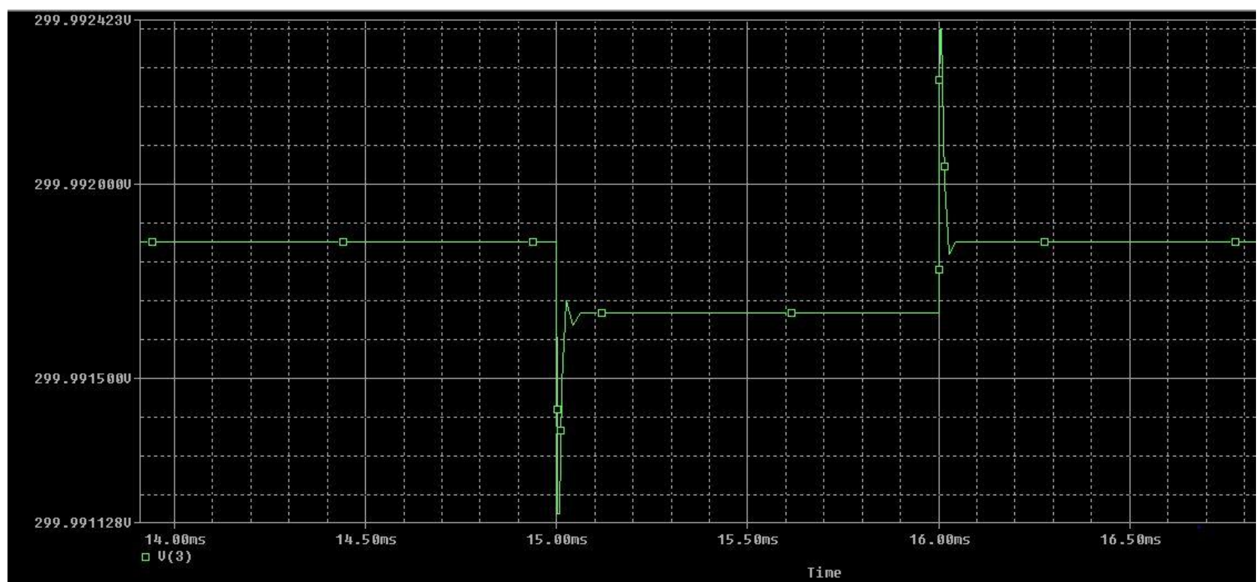


Multiplexed Drive Electronics



- Challenges:
  - Maintaining stable voltage on drive channel
  - Limit charge leakage
- Prototype of electronics constructed and ready to be tested with DM

PSPICE Simulation of single channel output



Thank You

Boston Micromachines Corporation is advancing MEMS deformable mirror technology to meet needs for spaced based Adaptive Optics systems through SBIR program

Acknowledgements

- Funding from NASA/JPL
  - SBIR Phase I # NNX10CE09P
  - SBIR Phase I # NNX10CE08P
- Mark Horenstein - Boston University Photonics Center